

# Friction Stir Weld Inspection Through Conductivity Imaging using Shaped Field MWM®-Arrays

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## Abstract

Friction Stir Welds (FSW) of Al 2195-T8 and Al 2219-T8, provided by Lockheed Martin Michoud Operations, were inspected for lack-of-penetration (LOP) defects using a custom designed MWM-Array, a multi-element eddy-current sensor. MWM® electrical conductivity mapping demonstrated high sensitivity to LOP as small as 0.75 mm (0.03 in.), as confirmed by metallographic data that characterized the extent of LOP defects. High sensitivity and high spatial resolution was achieved via a 37-element custom designed MWM-Array (Figure 1) allowing LOP detection using the normalized longitudinal component of the MWM measured conductivity. This permitted both LOP detection and correlation of MWM conductivity features with the LOP defect size, as changes in conductivity were apparently associated with metallurgical features within the near-surface layer of the LOP defect zone. MWM conductivity mapping reveals information similar to macroetching as the MWM-Array is sensitive to small changes in conductivity due to changes in microstructure associated with material thermal processing, in this case welding. The electrical conductivity measured on the root side of FSWs varies across the weld due to microstructural differences introduced by the FSW process, as well as those caused by planar flaws. Weld metal, i.e., dynamically recrystallized zone (DXZ), thermomechanically affected zone (TMZ), heat-affected zone (HAZ), and parent metal (PM) are all evident in the conductivity maps. While prior efforts had met with limited success for NDE of dissimilar alloy, Al2219 to Al2195 FSW, the new custom designed multi-element MWM-Array achieved detection of all LOP defects even in dissimilar metal welds.

## Introduction

New processes and products to enhance performance or safety of flight for the Space Shuttle program are a subject of continuing focus for NASA. Friction Stir Welding (FSW) is being implemented as part of Shuttle Upgrades to enhance safety and improve producibility of the External Tank (ET) manufactured by Lockheed Martin Space Systems – Michoud Operations in New Orleans, LA. Friction Stir Welding was invented and is licensed by TWI in Cambridge, UK [1]. FSW development has been performed at Marshall Space Flight Center (MSFC) from 1998 through 2001 for application to welding of the ET.

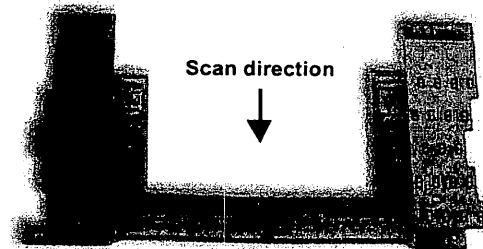


Figure 1. JENTEK 37-Element MWM-Array sensor

A solid state joining process, such as FSW, has numerous advantages over fusion welding including elimination of most consumable materials such as gas, filler wire and electrodes, as well as operating with far fewer primary welding variables to control. The 2XXX series aluminum alloys that comprise the ET enjoy improved strength at both room and cryogenic temperatures, as well as freedom from most of the conventional weld defects experienced in fusion welding. Fracture properties are also greatly improved and distortion is significantly reduced.

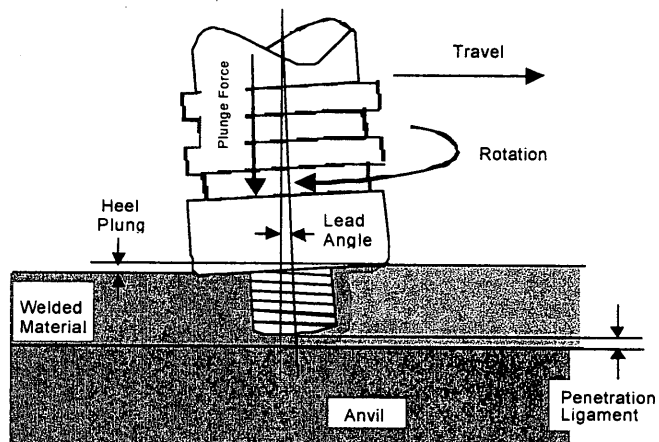
Al2195, a light-weight, high-strength, aluminum-copper-lithium (Al-Cu-Li) alloy was implemented in 1994 by Lockheed Martin as part of weight saving improvements to increase the performance of the Space Shuttle. The alloy has proven to be highly receptive to the FSW process, overcoming some of the production difficulties experienced in early development and implementation of Al2195 with conventional fusion weld processes [2].

## Friction Stir Welding

Friction Stir Welding for the ET is accomplished with a monolithic or multiple piece pin tool rotating at several hundred RPM and traversing a butt welded joint of the same design configuration used for fusion welding. A plunge load is imparted through a spindle, driven by a FSW machine or conventional mill, and reacted against a backside anvil. Frictional heating under the pin tool and around the pin tip generate sufficient heat to locally plasticize the aluminum alloys to be welded. Tool rotation during the FSW process imparts a material flow in three dimensions within the plasticized weld, causing complete mixing of the alloys, and consolidation of the weldment occurs via an

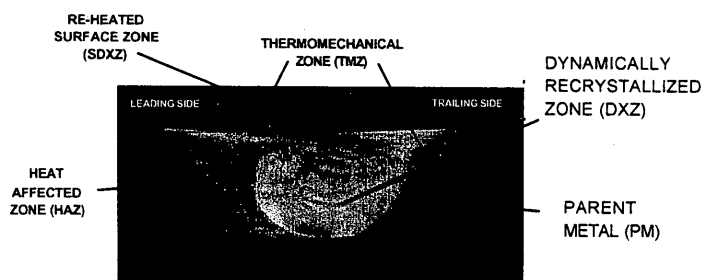
extruding/forging action under the pin tool shoulder as the pin tool is traversed down the length of the weld.

Figure 2 shows a schematic representation of the FSW process.



**Figure 2. Friction Stir Welding Process.**

Figure 3 provides a cross-section of a completed FSW allowing one to observe the metallurgical structure associated with a FSW of AL2195.

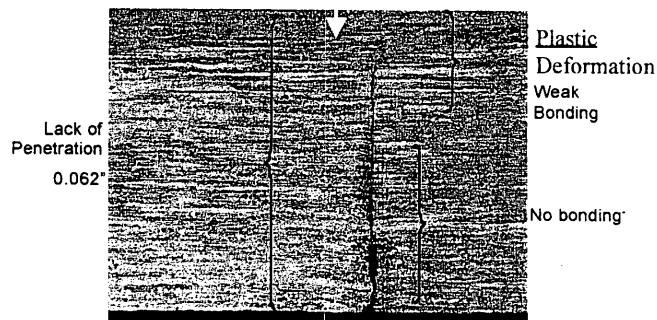
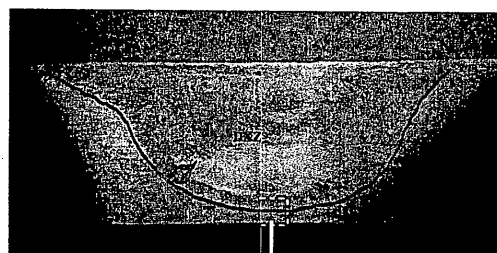


**Figure 3. Typical microstructure of full penetration FSW weld in 8.13 mm (0.320-in.) thick 2195-T8M4 Plate.**

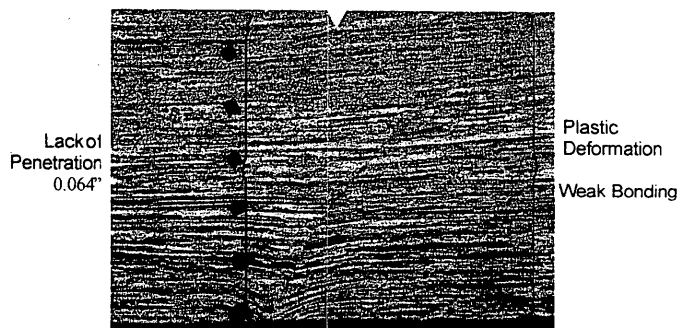
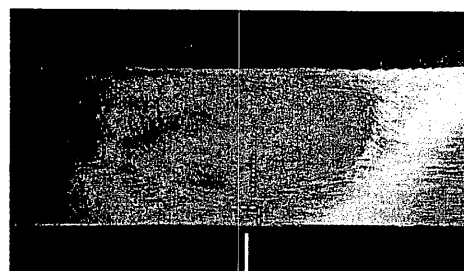
Metallurgical analysis of LOP indications has shown the distinct nature of the flaw is tied to the weld process itself. Factors affecting welding such as those which change heat input or heat flow affect the nature and degree of LOP present in the completed weldment.

A comparison of changes in the nature of the LOP is seen in Figures 4 and 5 where two different weld tools are used to perform FSW in the same alloy and thickness, yielding significantly different LOP features.

Distinctly different features include 1) total depth of LOP, 2) depth of plasticized material, and 3) degree of separation at the LOP interface (a.k.a. kissing bond). The latter feature proved to be particularly significant with regard to NDE, as it related directly to the ease and ability to detect LOP.



**Figure 4. LOP using "old" FSW Tooling.**



**Figure 5. LOP using "new" FSW Tooling.**

## FSW Nondestructive Evaluation

Commensurate with accomplishing weld process development, selection of appropriate NDE techniques is required to implement production Friction Stir Welding. Selection of NDE techniques requires consideration of Critical Initial Flaw Size(s) (CIFS), type(s) of potential flaws, and the maturity and production capability of candidate NDE techniques. Assessment of FSW mechanical properties and fracture properties has been completed to determine the basis for requirements [2]. In the development and selection of NDE for FSW a wide variety of NDE methods have been explored [3] including multiple liquid penetrants, several types of ultrasonic techniques, radiography, and both conventional eddy current and the newer MWM conductivity methods.

The promising results of conductivity methods paid off after both independent work by JENTEK Sensors, Inc. and a contract with JENTEK to adapt the MWM-Array technology specifically to the ET FSW application. This work provides significant risk mitigation for the ultrasonic, liquid penetrant and radiographic inspection techniques that will all be used in early ET production NDE.

### JENTEK Sensors MWM-Array Conductivity Measurement and Imaging

Reliable detection of relevant lack of penetration (LOP) during automated post weld inspection of Friction Stir Welds (FSWs) is critical to the integrity of the External Tank (ET) for the Space Shuttle. JENTEK Sensors, Inc. has worked with Lockheed Martin and NASA since 1998 to adapt their technology for ET FSW inspection. The most recent success in that effort has been the completion of design and demonstration of a custom sensor and inspection technique for detection of 1.25 mm (0.050-in.) and deeper LOP in Al2195-to-Al2195 and Al2219-to-Al2195 FSWs.

Figure 6 shows a laboratory setup used for demonstration of MWM-Array conductivity measurements as a means of FSW inspection including LOP detection and characterization as well as detection of planar flaws. The key components of the JENTEK system shown are: a Laptop computer with GridStation Software (1), Multi-channel impedance instrument (2) and MWM-Array probe with MWM-Array sensor tip (3). For the purposes of scanning the numerous FSW test panels used to evaluate the MWM technique, an automated Scanner (4) and custom, patented MWM-Array probe were used.

The goals during development of the JENTEK system, beyond the obvious detection capability, have been to provide a system that is practical and easy to use, robust in normal operation, rapid in automated scan mode, and capable of both automatic and manual scanning. To achieve these results, system calibration is initiated with air calibration and a multi-channel probe is used allowing up to 37 channels of data to be processed. Operation was based on automated scanning, but preserved with the ability to add a manual probe with encoders.



Figure 6. JENTEK MWM Inspection System.

The MWM-Array designed for this FSW application is a modification of a shaped-field array with multiple sensing elements. The position, number and arrangement of the individual sensing elements were customized within the MWM-Array for optimum detection. Figure 7 shows the details for the specific arrangement of the 37 sensing elements in order to achieve the resolution and accuracy required for inspection of FSW for LOP.

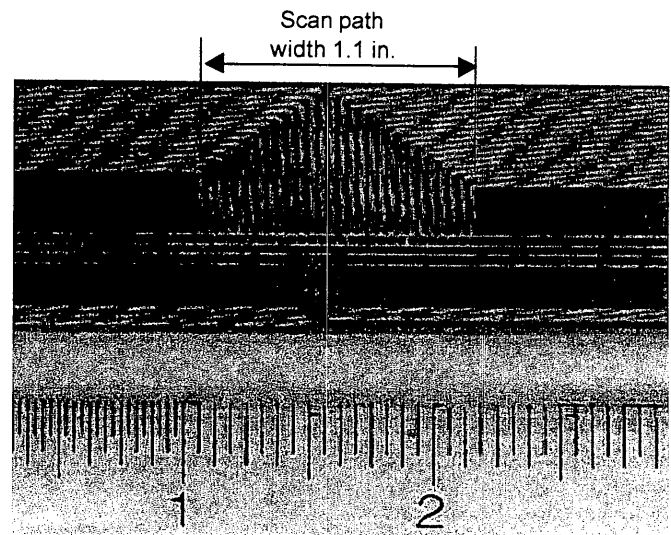


Figure 7. Detail view of elements in MWM-Array sensor.

The MWM-Array provides the capability to measure absolute electrical conductivity of the material. The electrical conductivity measured on the root side of the panels with FSWs varies across the weld due to microstructural differences introduced by the FSW process.

Both longitudinal and transverse scans were made for most panels in the study to assure complete coverage of the FSW and identify the optimum inspection technique. Conductivity images are based on the scanned data and processed to generate both C-scan images and profiles as shown in Figures 8 through 11.

The C-scan view presents the inspection data as a top down view of the Friction Stir Weld on the weld root side. The weld in Figure 8 extends from left to right and exhibits a circular region on the right edge of the image. The light band region in the center indicates the FSW weld nugget (DXZ), with the circular end region being the terminus of the weld.

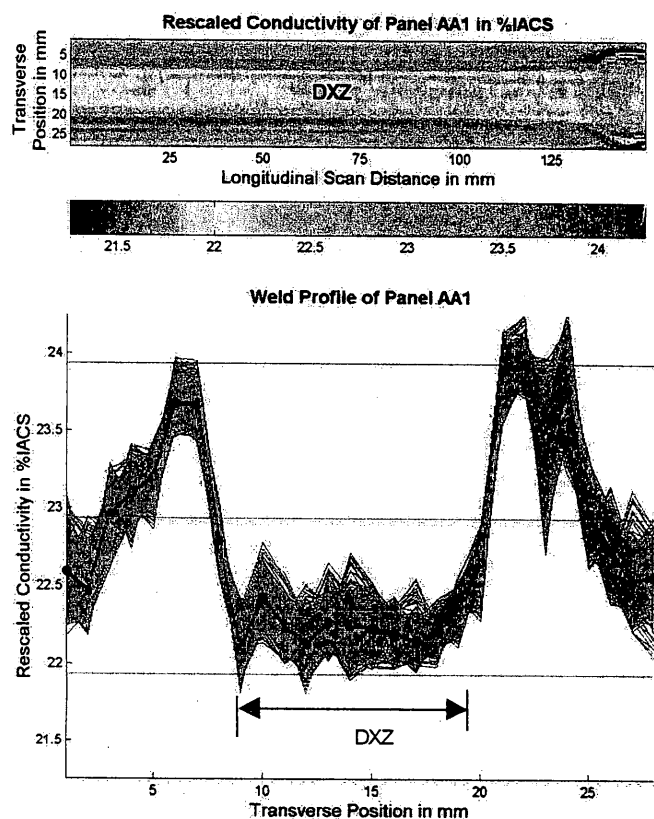


Figure 8. C-Scan image (top) and conductivity profile (bottom) of an acceptable similar metal FSW.

The conductivity profiles in Figures 8 and 9 are cross-section views of the inspection data for the similar metal FSWs. The location of the DXZ is indicated in the conductivity profile shown in Figure 8. Peaks in conductivity on either side of the DXZ profile indicate changing conductivity values associated with changes in the area of the weld, in this case, the TMZ and HAZ. The TMZ and HAZ in Figure 8 appear as relatively narrow zones alongside the FSW DXZ as viewed in the C-Scan.

LOP, the failure of the FSW to fully penetrate the joint thickness, presents itself as significantly different conductivity

patterns as illustrated in Figure 9. This FSW specimen contained 1.14 mm (0.045-in.) deep LOP and exhibits minimal DXZ, as well as several planar flaw indications.

Comparison of the profile in Figure 9 to that of Figure 8 reveals differences in conductivity values and their distribution, observed as changes in the shape of the profile. The presence of planar flaws is also noted as severe reductions (drop off) in the conductivity profile (at the center of the weld).

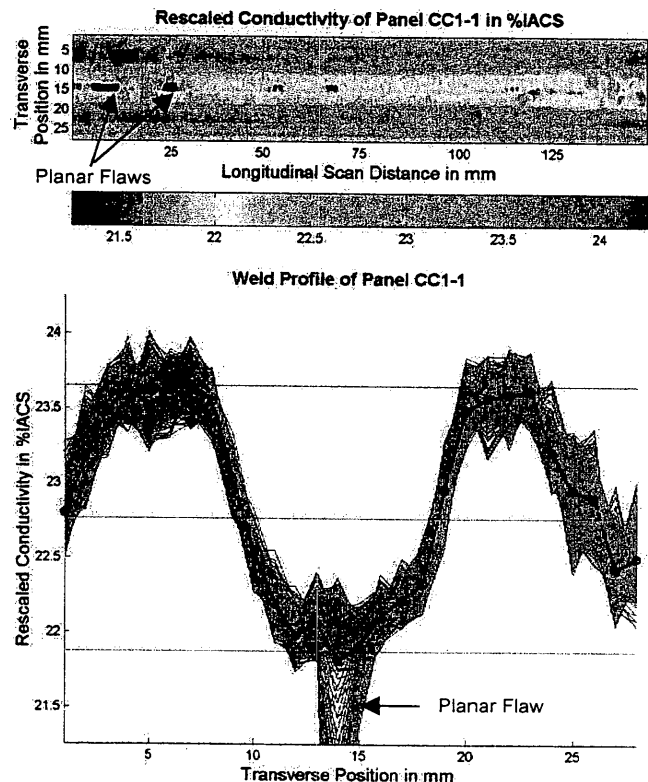


Figure 9. C-Scan image (top) and conductivity profile (bottom) for similar metal FSW with 1.14 mm (0.045-in.) LOP.

Dissimilar alloy FSWs yield quite different patterns of conductivity via the JENTEK MWM-Array technique, in part, due to the large differences in parent material conductivity. Al2219-T8 exhibits a typical conductivity of 34% IACS, while conductivity of Al2195-T8 is 20% IACS. Dissimilar metal FSWs free of LOP flaws appear as shown in Figure 10.

The C-Scan image in Figure 10 shows the weld extending left to right, however the extent of the FSW DXZ is not as easily seen as for similar alloy FSW like that of Figure 8. The conductivity profile is needed to assess the extent of the DXZ. The profile shows the high conductivity Al2219, to the left of the profile, decreasing rapidly as the conductivity drops into the DXZ area. The DXZ is bounded on either side by slight peaks in conductivity indicating a transition from the TMZ to the HAZ.

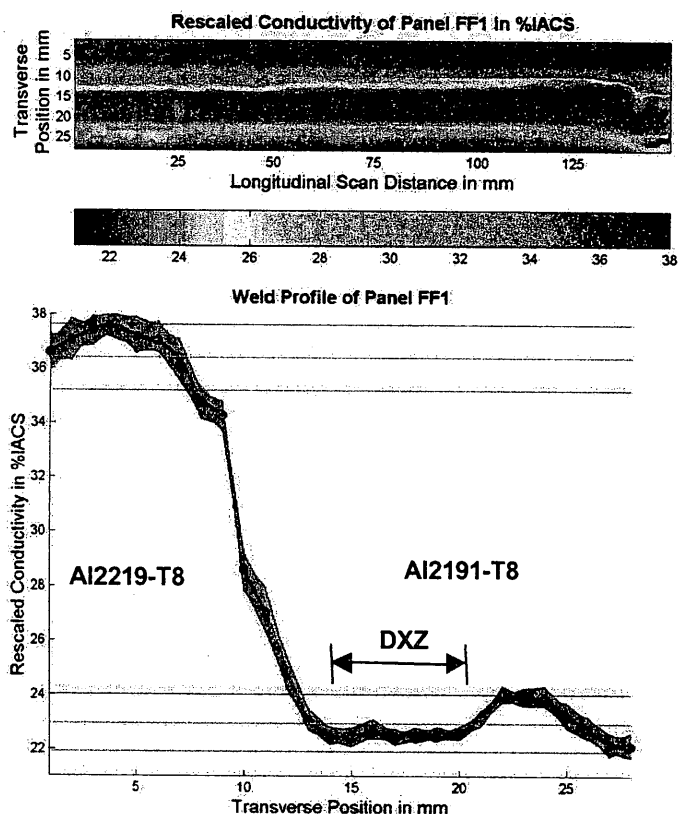


Figure 10. C-Scan image (top) and conductivity profile (bottom) for an acceptable dissimilar metal FSW.

An example of LOP in dissimilar alloy FSW is provided in Figure 11. The FSW for this example contained 1.45 mm (0.057-in.) deep LOP. Comparison of Figure 11 with Figure 10 provides visible differences that prove to be the key to developing criteria for detection of LOP. The differences affecting the shape of the conductivity map include a sharp increase in the slope (rate of decrease) of conductivity on the Al2219 side of the FSW and significantly reduced the extent of the conductivity minimum in the center of the weld.

Inspection data can be observed in different locations along the weld, allowing isolation of particular areas of interest. Note that the C-Scan image in Figure 11 indicates the presence of a planar flaw; however the conductivity profile (for a different region of the same weld) illustrates an area of typical LOP that is free of planar flaws. A profile isolated to this planar flaw region yielded the same sharp conductivity dropoff as that seen earlier in Figure 9 indicating a planar flaw.

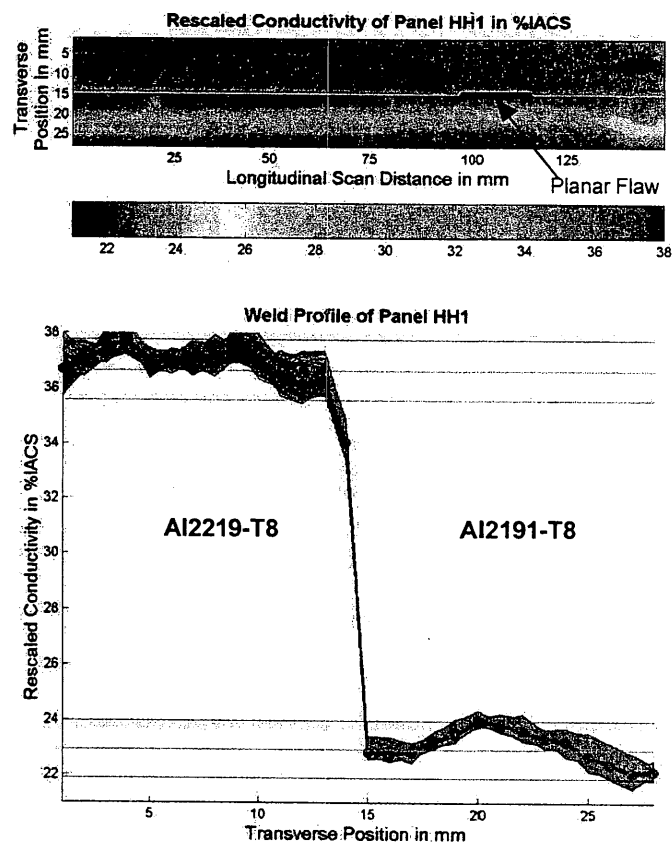


Figure 11. C-Scan image (top) and conductivity profile (bottom) for a dissimilar metal FSW with 1.45-mm (0.057-in.) LOP.

Such discrete planar flaws can be detected by other NDE methods as well. Evaluation of the MWM-Array inspection data reveals additional benefits, including information critical for assessment of the FSW quality and estimation of the depth of LOP detected. Figure 12 provides a correlation between LOP depth data and MWM measured midsection width, a weld feature identified in the evaluation algorithms.

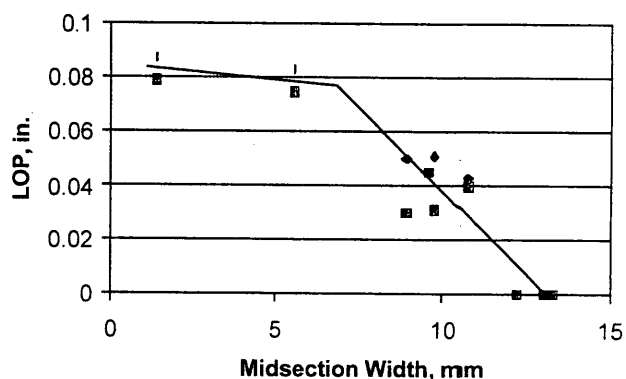


Figure 12. Correlation between midsection width and LOP depth.

## Summary

NASA and Lockheed Martin are pursuing implementation of Friction Stir Welding (FSW) for improved safety and producibility of the Space Shuttle External Tank (ET). FSW has been developed and demonstrated high strength, toughness, and defect-free welds in the 2XXX aluminum and aluminum-lithium alloys of the ET.

NDE inspection techniques for production use include multiple conventional methods such as liquid penetrant, radiography and ultrasonics. Innovative techniques, newly developed by JENTEK Sensors, have been completed to assure risk mitigation for ET inspection via demonstrating an MWM conductivity mapping technique and completing the adaptation of a custom 37-element MWM-Array sensor specific for ET FSW inspection.

JENTEK Sensors has demonstrated MWM-Array technology as an effective tool for FSW inspection, specifically for LOP defects. Detection of LOP as small as 0.75 mm (0.030-in.) deep LOP is possible in Al2195 FSW. Conductivity maps and GridStation software algorithms allow estimation of weld features and their correlation to LOP size.

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